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Measurement of the Decay $B^- \to D^{*0} e^- \overline{\nu}_e$

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Using 226 million $B\overline{B}$ events recorded on the $\Upsilon(4S)$ resonance with the *BABAR* detector at the SLAC e^+e^- PEP-II storage rings, we reconstruct $B^- \to D^{*0} e^- \overline{\nu}_e$ decays using the decay chain $D^{*0} \to D^0\pi^0$ and $D^0 \to K^-\pi^+$. From the dependence of their differential rate on w, the dot product of the four-velocities of B^- and D^{*0}, and using the form factor description by Caprini *et al.* with the parameters $F(1)$ and $\rho^2_{A_1}$, we obtain the results $\rho^2_{A_1} = 1.16 \pm 0.06 \pm 0.08$, $F(1) \cdot |V_{cb}| = (35.9 \pm 0.6 \pm 1.4) \cdot 10^{-3}$, and $\mathcal{B}\left(B^- \to D^{*0} e^- \overline{\nu}_e\right) = (5.56 \pm 0.08 \pm 0.41)\%$.

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The Standard Model of particle physics (SM) contains a large number of free parameters which can only be determined by experiment. Precision measurements of all of these parameters are essential for probing the validity range of the model by comparing many other precision measurements with SM calculations. One of the SM parameters, the element $|V_{cb}|$ of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix, is determined with semileptonic B-meson decays. Their rates Γ are given by the universality of the weak interaction (the Fermi constant G_{F}), by quark mixing ($\Gamma \propto G_{\mathrm{F}}^2|V_{cb}|^2$), and by strong-interaction corrections calculated in heavy-quark effective QCD. For the exclusive decays $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell$ and $B^- \to D^{*0}\ell^-\overline{\nu}_\ell$ ($\ell = e, \mu$), these corrections are expressed as form factors in the differential rate $\mathrm{d}\Gamma/\mathrm{d}w$, where w is the dot product of the four velocities of the B and the D^*. The form factors depend on the three parameters ρ^2, $R_1(1)$, and $R_2(1)$ [1]. Whereas the $\overline{B}^0$ mode has been measured by many experiments [2], the B^- mode has only been measured by two groups [3, 4] with much smaller data samples. However, the $\overline{B}^0$ experiments do not agree well in their ρ^2 results. Using the isospin symmetry $\mathrm{d}\Gamma(B^- \to D^{*0}\ell^-\overline{\nu}_\ell) = \mathrm{d}\Gamma(\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell)$, a precision measurement of the B^- mode can improve knowledge of ρ^2 and consequently of Γ and $|V_{cb}|$.

The aim of our analysis [5] is the determination of the differential decay fraction $\mathrm{d}\mathcal{B}(B^- \to D^{*0}e^-\overline{\nu}_e)/\mathrm{d}w$, where $\mathcal{B} = \Gamma\tau$, with the B^- lifetime τ. The neutrino in the $B^- \to D^{*0}e^-\overline{\nu}_e$ decay is not reconstructed. Therefore, the w value of each reconstructed event cannot be obtained, only an approximation $\tilde{w}$ as defined below. Instead of unfolding $\mathrm{d}\mathcal{B}/\mathrm{d}\tilde{w}$, the parametrized $\mathrm{d}\mathcal{B}/\mathrm{d}w$ expectation convolved with the w resolution from Monte Carlo (MC) simulation is fitted to the observed $\mathrm{d}\mathcal{B}/\mathrm{d}\tilde{w}$ distribution. The fit uses the parametrization of Caprini et al. [1] with $\rho^2 \equiv \rho^2_{A_1}$ and determines the two parameters $F(1) \cdot |V_{cb}|$ and ρ^2. The decay fraction $\mathcal{B}$ is obtained by integrating $\mathrm{d}\mathcal{B}/\mathrm{d}w$. Using the notations $\Delta M \equiv m_B - m_{D^*}$, $r \equiv m_{D^*}/m_B$, and $z \equiv (\sqrt{w+1} - \sqrt{2})/(\sqrt{w+1} + \sqrt{2})$, the parametrization is defined by the following expressions:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}w} = \frac{G_{\mathrm{F}}^2|V_{cb}|^2}{48\pi^3}(\Delta M)^2 m_{D^*}^3 \sqrt{w^2-1}\,(w+1)^2\, g(w) F^2(w),$$

$$g(w) = 1 + \frac{4w}{w+1}\frac{m_B^2 - 2wm_Bm_{D^*} + m_{D^*}^2}{(\Delta M)^2},$$

$$F^2(w) = \frac{|h_{A_1}(w)|^2}{g(w)} \sum_{i=0,+,-} \left|\tilde{H}_i(w)\right|^2,$$

$$\tilde{H}_0(w) = 1 + \frac{w-1}{1-r}\left[1 - R_2(w)\right],$$

$$\tilde{H}_\pm(w) = \frac{\sqrt{1-2wr+r^2}}{1-r}\left[1 \mp \sqrt{\frac{w-1}{w+1}} R_1(w)\right]$$

$$\frac{h_{A_1}(w)}{h_{A_1}(1)} = 1 - 8\rho^2 z + \left(53\rho^2 - 15\right) z^2 - \left(231\rho^2 - 91\right) z^3,$$

$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2,$$

$$R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2,$$

with $F(1) = h_{A_1}(1)$. The values of $R_{1,2}(1)$ are not determined in this analysis; they are taken from Ref. [6].

For our analysis, we use $205\,\mathrm{fb}^{-1}$ of e^+e^- annihilation data recorded at $\sqrt{s} \approx m(\Upsilon(4S))$ with the BABAR detector [7] at the SLAC PEP-II storage rings [8]. In addition to these on-peak data, we also use $16\,\mathrm{fb}^{-1}$ of off-peak data collected 40 MeV below the $\Upsilon(4S)$ resonance. We select $B^- \to D^{*0}e^-\overline{\nu}_e$ candidates [9] by pairing electrons with $p^* > 1.2\,\mathrm{GeV}/c$ in the e^+e^- rest frame (cms) with D^{*0} candidates. Since the precision of our results is not statistically limited, we restrict the analysis to the sequential decay modes $D^0 \to K^-\pi^+$, which has the smallest combinatorial background, and $D^{*0} \to D^0\pi^0$, which has a better resolution in $\Delta m \equiv m(K^-\pi^+\pi^0) - m(K^-\pi^+)$ than $D^{*0} \to D^0\gamma$.

Charged particles are selected if they have at least 10 hits in the drift chamber, transverse momentum $p_T > 0.1\,\mathrm{GeV}/c$, and a polar angle between 23.5° and 145.5° in the laboratory frame. Electrons (kaons) are selected with tight (loose) particle identification criteria [10]. Neutral pions are reconstructed from two photons, each with energy above 30 MeV and a photon-compatible lateral shower shape in the calorimeter. The two photons must be consistent with the π^0 hypothesis ($115 < m_{\gamma\gamma} < 150\,\mathrm{MeV}/c^2$). A kinematic fit with the constraint $m_{\gamma\gamma} = m_{\pi^0}$ improves the Δm resolution by a factor of 3. The decay candidates have to fulfill the following additional requirements: the D^{*0}-D^0 mass difference and the D^0-candidate mass must satisfy $135 < \Delta m < 153\,\mathrm{MeV}/c^2$ and $1.8496 < m(K^-\pi^+) < 1.8796\,\mathrm{GeV}/c^2$, respectively. To reject non-B-decay candidates, the second normalized Fox-Wolfram moment [11] of the event has to be smaller than 0.45. To help reject combinatorial background with a D^{*0} and an e^- from different B mesons in the event, the cms angle between them must be larger than 90°.

Since there are many low-energy background photons, the selection criteria result in many events with two or more $D^{*0}e$ candidates, on average 1.75 per event. All $D^{*0}e$ candidates in the same $eK\pi$ combination form one group, called a candidate group. On average there are 1.015 candidate groups per event. When an event has more than one candidate group, we keep only the one with the best $|m(K\pi) - m(D^0)|$. All candidates in one group are kept in the analysis because the simulation of low-energy photons is not perfect. This procedure ensures that correctly reconstructed candidates are selected with the same probability in data and MC simulation.

The surviving candidates are binned in Δm, $\cos\theta^*_{\mathrm{BY}}$,

and $\tilde{w}$. The first two variables are used for signal-background separation, and the third is used for the w dependence of the signal. The mass difference Δm is defined above, and $\theta^*_{\rm BY}$ is the angle between the B meson and the $Y = D^{*0} + e$ system in the cms defined by

$$p_\nu^2 = 0 = m_{\rm B}^2 + m_{\rm Y}^2 - 2(E^*_{\rm B} E^*_{\rm Y} - |\vec{p}^{\,*}_{\rm B}||\vec{p}^{\,*}_{\rm Y}|\cos\theta^*_{\rm BY}) \ .$$

The value of

$$w = w(\beta^*) \equiv (E^*_{\rm B} E^*_{\rm D^*} - |\vec{p}^{\,*}_{\rm B}||\vec{p}^{\,*}_{\rm D^*}|\cos\beta^*)\,/\,(m_{\rm B} m_{\rm D^*})$$

cannot be determined since the angle β^* between the B and the D^{*0} in the cms is unknown. However, β^* is bounded by a minimum and a maximum value and we use $\tilde{w} = [w(\beta^*_{\rm min}) + w(\beta^*_{\rm max})]/2$ as an estimator for w. Both w and $\tilde{w}$ range from 1.0 to 1.5, and the distribution of $\tilde{w} - w$ is nearly Gaussian with an RMS of 0.026.

The fit for $V = F(1)|V_{cb}|$ and ρ^2 is a binned maximum-likelihood fit with 41, 14, and 10 equidistant bins in Δm, $\cos\theta^*_{\rm BY}$, and $\tilde{w}$, respectively. The fit function in each $\tilde{w}$ bin is the sum of the signal function $S_{\tilde{w}}(V,\rho^2)$ and 23 background functions $B_{i,\tilde{w}}(V,\rho^2)$. Each summand is taken as the product of one-dimensional functions of Δm and $\cos\theta^*_{\rm BY}$. The Δm distributions of correctly (wrongly) reconstructed D^{*0} mesons are parametrized by the sum of 3 bifurcated Gaussians (product of an exponential and a power law function). The $\cos\theta^*_{\rm BY}$ distributions are modeled by modified KEYS functions [5].

The factor functions of $S_{\tilde{w}}$ are obtained from fits to the reweighted signal MC distributions with V-, ρ^2-, $R_1(1)$-, and $R_2(1)$-dependent weights on the generator level. $S_{\tilde{w}}$ also includes the total number of produced $B\overline{B}$ pairs, all decay fractions of sequential decays, the B^- lifetime, all MC reconstruction efficiencies, and efficiency corrections. The corrections for track reconstruction and charged-particle identification are obtained from control data samples and their MC expectations. The correction of the π^0 reconstruction efficiency is described below. Small corrections are also applied for deviations of the shapes of the Δm distributions in data and MC because of track resolution differences, and for deviations in the shapes of the $\cos\theta^*_{\rm BY}$ distributions because of differences in storage-ring energy calibration and resolution.

The background functions are separately determined for the 23 background classes [5]. The large number of backgrounds is necessary in order to factorize all $B_{{\rm i},\tilde{w}}$ as $B_{1,{\rm i},\tilde{w}}(\Delta m) \times B_{2,{\rm i},\tilde{w}}(\cos\theta^*_{\rm BY})$. The one-dimensional fit functions $B_{j,{\rm i},\tilde{w}}$ are again obtained from fits to MC distributions. The fit to the data has 49 free parameters; V, ρ^2, and 47 for adjustments of Δm shapes, $\cos\theta^*_{\rm BY}$ shapes, and background fractions. The number of $e^+e^- \to c\overline{c}$ background events is fixed by the off-peak data.

As validation of the fit procedure, we perform our fit on five different MC subsamples whose size corresponds to that of the data sample. All five results for V and ρ^2 agree with the MC input to within one standard deviation. Applied to the data and using the input-parameter values in Table I, the fit result is $V = (35.9 \pm 0.6)\cdot 10^{-3}$ and $\rho^2 = 1.16 \pm 0.06$ with a correlation coefficient of $+0.90$. The result leads to $\mathcal{B} = (5.56 \pm 0.08)\%$ after integrating $d\mathcal{B}/dw$. The total number of signal events is $23\,499 \pm 329$. A control value of χ^2 can be calculated after the fit as a goodness-of-fit measure. We find 4436.3 for 4095 degrees of freedom after rebinning in regions with low statistics. The values of χ^2 in the MC-subsample fits are of similar size indicating that the factorization assumptions for $S_{\tilde{w}}$ and $B_{i,\tilde{w}}$ are not perfect. Since there is no bias in V or ρ^2 in the MC-subsample fits and no significant correlation between background parameters and both V and ρ^2 in the fit to the data, we conclude that the results are unbiased.

TABLE I: Summary of input parameter values.

Input Parameter	Value	Ref.
$\mathcal{B}\left(\Upsilon(4S) \to B^+B^-\right)$	$(50.6 \pm 0.8)\%$	[12]
$\mathcal{B}\left(D^{*0} \to D^0\pi^0\right)$	$(61.9 \pm 2.9)\%$	[12]
$\mathcal{B}\left(D^0 \to K^-\pi^+\right)$	$(3.80 \pm 0.07)\%$	[12]
$\mathcal{B}\left(\pi^0 \to \gamma\gamma\right)$	$(98.798 \pm 0.032)\%$	[12]
τ_{B^-}	(1.638 ± 0.011) ps	[12]
$R_1(1)$	1.429 ± 0.075	[6]
$R_2(1)$	0.827 ± 0.044	[6]

Figure 1 shows the result of the fit together with the selected data. The "Signal" part of the fit function contains the correctly reconstructed $B^- \to D^{*0}e^-\overline{\nu}_e$ decays. The two D^{**} parts contain $B \to D^{**}e\nu$ decays with ("Δm peaking") and without ("Δm flat") a correctly reconstructed D^{*0} intermediate state ($D^{**} = D_1, D_0^*, D'_1, D_2^*, D^*\pi, D\pi$). Events with a correctly reconstructed D^{*0} and a correctly identified electron from the same B and from two different B mesons are in the "Correlated" and "Uncorrelated" background parts, respectively. "Signal-like" are true decays $B^- \to D^{*0}e^-\overline{\nu}_e$ and $\overline{B}^0 \to D^{*+}e^-\overline{\nu}_e$ which are not correctly reconstructed. The background from true $B \to D^0 e\nu$ decays is called "$D^0 e\nu$". All other background candidates from $B\overline{B}$ events ("Combinatorial D^{*0}") are flat in the Δm and the $\cos\theta^*_{\rm BY}$ distributions since they do not contain a correctly reconstructed D^{*0} and they do not come from a charmed semileptonic decay. The last contribution, only visible at high $\tilde{w}$, comes from $c\overline{c}$ events.

To determine the systematic uncertainties listed in Table II we either rerun the fit with varied input or we rescale the fit result. The upper part of the Table gives the "internal" uncertainties which are specific to our analysis. The relative uncertainty on the efficiency to reconstruct a track is 0.8%, leading to 2.4% and 1.2% for $\mathcal{B}$ and V. The dependence of the tracking efficiency on the transverse momentum p_T has an uncertainty which could distort the shape of the $\tilde{w}$ spectrum. The uncertainties arising from the identification (ID) of charged tracks as electrons or as kaons contribute to the result as

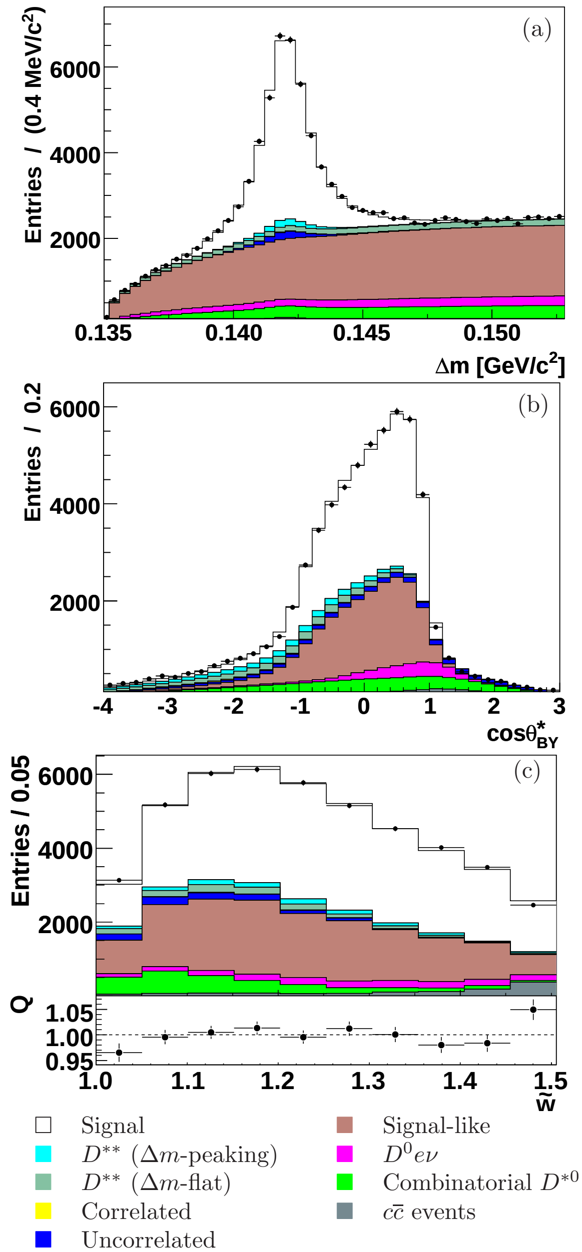

FIG. 1: (Color online). Data distributions (dots with error bars) and fit results (stacked histograms) for (a) Δm in the $\cos\theta^*_{\rm BY}$ signal range $(-1,+1)$, (b) $\cos\theta^*_{\rm BY}$ in the Δm signal range (140,144 MeV/c^2), and (c) $\tilde{w}$ in both signal ranges. The plot below (c) shows the quotient fit/data. The different contributions to the fit function are explained in the text.

listed under "particle ID efficiency". A significant fraction of the total uncertainty comes from the precision of the π^0 reconstruction efficiency (ϵ_{π^0}). It is determined from $e^+e^- \to \tau^+\tau^-$ events where one of the two τ leptons is either reconstructed by one track and two clusters (mainly $\tau \to \rho(\pi\pi^0)\nu$) or by only one track without clusters (mainly $\tau \to \pi\nu, \mu\nu\overline{\nu}$). The other τ, used as a τ-pair tag, is reconstructed in its $e\nu\overline{\nu}$ decay. From the numbers

TABLE II: Relative systematic uncertainties in percent.

	$\Delta V/V$	$\Delta\rho^2/\rho^2$	$\Delta\mathcal{B}/\mathcal{B}$
Tracking efficiency ($\epsilon_{\rm tr}$)	1.2	-	2.4
p_T dependence of $\epsilon_{\rm tr}$	0.3	0.5	0.2
Particle ID efficiency	0.9	2.0	1.6
Extrapolated π^0 efficiency (ϵ_{π^0})	1.8	-	3.6
p_{π^0} dependence of ϵ_{π^0}	1.0	3.5	0.4
Δm shape of D^{**} background	0.1	0.1	0.2
Shape parameters	1.0	2.5	0.6
Number of $B\overline{B}$ events	0.6	-	1.1
Off-peak luminosity	0.1	0.4	<0.1
MC statistics	0.3	0.8	0.2
Radiative corrections	0.5	0.4	1.4
Total internal	2.9	4.9	5.0
$R_1(1)$ and $R_2(1)$	0.4	4.7	0.5
$\mathcal{B}\left(\Upsilon(4S) \to B^+B^-\right)$	0.8	-	1.6
$\mathcal{B}\left(D^{*0} \to D^0\pi^0\right)$	2.3	-	4.7
$\mathcal{B}\left(D^0 \to K^-\pi^+\right)$	0.9	-	1.8
B^- life time	0.3	-	-
D^{**} decay fractions	0.3	0.7	0.3
Number of D^{*0} in $c\overline{c}$ events	0.2	0.7	<0.1
Total external	2.7	4.8	5.3
Total	3.9	6.8	7.3

of $\tau^+\tau^-$ events reconstructed in each of the two channels we derive an efficiency in data and in MC, giving a correction to the simulated π^0 efficiency. The correction is obtained for momenta above 350 MeV/c and has a precision of 3%. In the lower-momentum region with all π^0 mesons from $D^{*0}e\nu$ decays, we use a correction factor of 0.960 ± 0.035 where the increased uncertainty covers the extrapolation into this region. Efficiency differences between $\tau^+\tau^-$ and $B\overline{B}$ events are covered by the MC simulation as controlled by comparing the rates of reconstructed D^0 decays into $K^-\ \pi^+$ and $K^-\ \pi^+\ \pi^0$. The uncertainty in the shape of the $\tilde{w}$ spectrum, i.e. its influence on ρ^2, is estimated by fit results for different lower cuts on p_{π^0} ("p_{π^0} dependence of ϵ_{π^0}"). Corrections to the Δm shape and to the $\cos\theta^*_{\rm BY}$ shape are parametrized as functions of $\tilde{w}$, see "shape parameters" for their contributions to the systematics. Uncertainty estimates from radiative corrections are taken from the *BABAR* analysis of $B^0 \to D^*\ell\nu$ decays [6] which uses the same lepton-momentum cutoff of 1.2 GeV/c.

The "external" uncertainties owing to parameters taken from other experiments are given in the lower part of Table II. For ρ^2 they are dominated by $R_1(1)$ and $R_2(1)$. For future updates, we also give in Table III the derivatives of our three results with respect to these two variables as determined from fits with varied input values. The $B \to D^{**}e\nu$ decays contribute to the uncertainties because of their less precisely known decay fractions and their uncertain Δm shape due to low-energy photon background. Uncertainties in their $\tilde{w}$ shape are covered by 10 of the 49 fit parameters.

TABLE III: Derivatives of V, ρ^2, and $\mathcal{B}$.

	V	ρ^2	$\mathcal{B}$
$\partial/\partial R_1(1)$	-0.00342	$+0.0303$	-0.00567
$\partial/\partial R_2(1)$	-0.00525	-1.22	-0.00594

Adding all systematic uncertainties in quadrature leads to the last line in Table II and to our final results

$$F(1) \cdot |V_{cb}| = (35.9 \pm 0.6 \pm 1.4) \cdot 10^{-3} \ ,$$
$$\rho^2_{A_1} = 1.16 \pm 0.06 \pm 0.08 \ ,$$
$$\mathcal{B}(B^- \to D^{*0} e^- \overline{\nu}_e) = (5.56 \pm 0.08 \pm 0.41)\% \ .$$

The correlation coefficients between $F(1) \cdot |V_{cb}|$ and $\rho^2_{A_1}$ are $+0.90$ for statistics, $+0.42$ for systematics, and $+0.52$ in total. Using $F(1) = 0.919 \pm 0.033$ from lattice QCD [13], we obtain $|V_{cb}| = (39.0 \pm 0.6 \pm 2.0) \cdot 10^{-3}$ in good agreement with the average from the exclusive neutral B decays $B^0 \to D^{*-}\ell^+\nu$, $(39.2 \pm 0.7 \pm 1.4) \cdot 10^{-3}$ [2], and in agreement with results from the inclusive decays $B \to X_c \ell \nu$, e. g. $(42.0 \pm 0.2 \pm 0.7) \cdot 10^{-3}$ in Ref. [14]. Our result for ρ^2 is in the center of the range (0.5, 1.5) from the $B^0 \to D^{*-}\ell^+\nu$ experiments [2].

Compared with the PDG average [12] of $\mathcal{B}(B^- \to D^{*0} e^- \overline{\nu}_e)$, our result is lower by more than 1.5 standard deviations. For a comparison of our decay-fraction result with that of the B^0 mode, we use $\tau(B^+)/\tau(B^0) = 1.076 \pm 0.008$ and $\mathcal{B}(B^0 \to D^{*-}\ell^+\nu) = (5.28 \pm 0.18)\%$ [2]. This gives $\mathcal{B}(B^- \to D^{*0}\ell^-\overline{\nu}) = (5.68 \pm 0.20)\%$; our result agrees well with this value.

To conclude, this measurement is the first one for $B^- \to D^{*0}\ell^-\overline{\nu}_\ell$ decays with a data sample comparable to recent $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell$ experiments. The results for the decay rate and for $|V_{cb}|$ agree well with the $\overline{B}^0$ mean values. Since the uncertainties in the reconstruction of low-momentum π^+ and π^0 are experimentally very different, the agreement of our ρ^2 result with the central value of the $\overline{B}^0$ results provides a crucial cross check for previous $|V_{cb}|$ determinations in $B \to D^*\ell\nu_\ell$ decays.

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